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Decay and capture of mesons in photographic emulsions

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DECAY AND CAPTURE OF MESONS IN PHOTOGRAPHIC EMULSIONS

by

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I. INTRODUCTION

Mesons were first predicted by Yukawa in 1935. The first experimental evidence was given by Anderson during 1937 based upon cloud chamber photographs and range measurements of penetrating particles. In spite of the period of several years that have elapsed since the first discovery of the meson, the amount of experimental data regarding the capture and decay of mesons is still quite meager. This lack of data has not been due to a lack of interest by experimentalists in problems connected with mesons, but rather to several factors which have made experimental studies somewhat difficult. Probably the most important factor has been the relatively low flux of mesons which was available for study. Initially, mesons were only available as a component of the cosmic radiation. With the advent of artificial production of mesons by high energy accelerators, the problem of intensity has essentially been overcome. However, the background of radiation in the vicinity of the accelerators is excessively high for some studies. In the case of a few problems, where the background of electrons must be kept low, the flux of mesons from an accelerator is about the same as from the cosmic radiation. For this reason it was decided to obtain mesons for the present study from the cosmic radiation.

It is well known, from cloud chamber and nuclear emulsion studies, that mesons are unstable and decay. However a competitive process occurs for negative mesons, namely, nuclear capture.

Several interesting questions arise. What percentage of the negative μ mesons are captured and do not decay in nuclear emulsions? Do mesons undergo nonradiative transitions, such as Auger transitions, with the ejection of electrons of sufficient energy to be detectable in photographic emulsions? Do π and μ mesons interact with the orbital electrons in the same way? Are the residual nuclei of π meson disintegrations highly β active? The following discussion describes certain studies of these and other phenomena associated with the decay and capture of mesons in photographic emulsions.

Meson events were obtained in photographic emulsions by exposing nuclear track plates to the cosmic radiation in the stratosphere. The plates were carried aloft by meteorological balloons inflated with helium. The balloon flights are described in detail in section III.

After the plates were recovered and developed, they were searched for meson events under a microscope. Meson tracks ending in the emulsion were catalogued and classified by the characteristics of the tracks and by the phenomena at the end of the tracks.

Low energy electrons were found to be associated with the μ mesons which were captured. The number of these electrons and the energy distribution were studied.

Stars produced by negative π mesons were studied to see if the percentage and energy distribution of the low energy electrons from these stars are the same as from μ mesons.

In order to determine the energy of the low energy electrons, nuclear track plates were exposed to monoenergetic electrons. By measuring the ranges of the monoenergetic electrons, an energy range relationship at low energies was determined for electrons in the emulsion. The energy resolution for electrons in the emulsion was determined from the variation of the range of the monoenergetic electrons.

II. LITERATURE SURVEY

The effect of charged particles on photographic emulsions has been known for some time, originating with the studies of Becquerel[1] who found that photographic plates were blackened by radiations from minerals containing uranium. However, individual tracks due to charged particles were not studied; only the opacity of the film was noted.

Blau[2] was the first to utilize photographic emulsions to study the tracks produced by individual charged particles. Conventional "half tone" plates were used to study proton and alpha particle tracks from natural radioactive elements and from nuclear reactions. The grain density along the tracks of the particles was very low, with the result that the resolution of the emulsions was much lower than the resolution of the existing cloud chambers.

The development of the present nuclear emulsions is due mainly to the efforts of Powell[3] and Rotblot working in conjunction with Ilford of England. Powell[4] and the group at Bristol very early pointed out the many applications of nuclear emulsions to the fields of nuclear physics and cosmic rays. The characteristics of the emulsions have been investigated by many workers. Sorensen[5] made a careful study of the determination of the charge of particles in photographic emulsions by means of delta ray counting. Lamb and Brown[6] and Yagoda[7] have made a study of the factors affecting the fading of the latent image in nuclear track plates. This information is important in connection with grain counting in emulsions. The importance of non-uniform shrinkage of the emulsion was pointed out by Rotblot and Tai[8].

The characteristics of electron sensitive emulsions were first given by Brown, Camerini, Fowler, Muirhead and Powell[9]. The many advantages of the electron sensitive emulsions over the previous emulsions are described. The range-energy relationship for electrons in electron sensitive emulsions has been determined by Zajac and Ross[10] and by Hertz[11].

A very successful technique for developing very thick emulsions was devised by Blau[12]. A similar method, but one based upon different principles, was developed by the group at Brussels and is described in an article of Dilworth, Occhialini and Payne[13]. Experimental evidence for a particle of mass between an electron and a proton was first given by

Neddermeyer and Anderson[14] and by Young and Street[15]. Conclusive evidence for particles of mass between that of an electron and a proton, based upon cloud chamber photographs, was given by Neddermeyer and Anderson[16]. Rasetti[17] concluded from a study of the absorption of mesons in various materials, that mesons are radioactive and decay into electrons. Evidence for the existence of two types of mesons was first given by Lattes, Occhialini, and Powell[18]. A further study by Occhialini and Powell[19] of mesons tracks in photographic emulsions led to the discovery that stars were produced in many cases by the capture of π mesons. Chang[20] has made a careful study of the capture of μ mesons in thin foils of Pb inside a cloud chamber. His studies show quite conclusively that no high energy γ rays are emitted upon capture of μ mesons in Pb.

Wheeler[21] presented theoretical evidence for the ejection of Auger electrons from the atomic capture of mesons in certain elements. Powell[9] concluded, from observations of the number of low energy electrons from π stars, that the number of Auger transitions which give rise to electrons seen in nuclear plates must be very small. A more thorough study was made by Cosyns, Dilworth, Occhialini and Schoenberg[22] and by Bonetti[23], who found that low energy electrons are associated with the capture of μ mesons.

III. BALLOON FLIGHTS

Early in the program, it became apparent that a large number of meson events was required in order to obtain reasonable statistics concerning the number of low energy electrons associated with μ mesons. The intensity of low energy mesons at different altitudes was determined by Lord and Schein[24]. It was quite apparent that flights must be made to altitudes greater than 50,000 feet if a reasonable number of mesons in each nuclear plate were to be obtained. The time required to search a nuclear track plate is almost independent of the number of meson events present in the plate. Any increase in the number of mesons in each plate would correspondingly decrease the searching time. For this reason, considerable effort was made to increase the exposure time at high altitudes.

Meteorological balloons, made of neoprene, were readily available which could lift several hundred grams of equipment to an altitude of about 90,000 feet. Since they were comparatively inexpensive, several attempts were made to obtain flights which would remain above 50,000 feet for several hours.

For a given type of balloon the bursting diameter is fixed. The balloon expands until the pressure inside the balloon is nearly the same as the outside pressure, consequently the bursting altitude is determined by the amount of gas in the balloon. The amount of gas is in turn fixed by the weight of the equipment and the rate of ascension of the balloon. As a result, the bursting altitude is essentially determined by the weight of the equipment for a given type of balloon. However, if the equipment is extremely light in comparison with the weight of the balloon, a decrease in the weight of the equipment will not materially increase the bursting altitude. In the majority of the balloon flights where the pressure measuring instruments were not included, the weight of the photographic plates, container, etc. was about one third of the weight of the large balloon. For this reason, the weight was not seriously considered in the design of the equipment.

In the first flights, pressure recording instruments were included along with the plates. By converting the atmospheric pressure into altitude by the use of standard atmospheric charts, nearly all of the essential characteristics of the balloon flights were obtained. A conventional meteorological baroswitch was modified by removing the commutator and replacing it with a drum, driven by a spring actuated clock. A strip of waxed paper was secured to the drum. The sharp pen of the baroswitch made a visible scratch on the waxed paper as the drum was turned by the clock. The baroswitch was calibrated by placing the entire equipment in an evacuated bell jar and measuring the deflection as a function of the pressure.

The nuclear track plates were enclosed in a light tight cardboard box and placed, along with the pressure measuring device, inside a waxed cardboard container. Ten dollars was given for the return of the equipment. Since the plates accumulated a background of electron tracks in a few weeks, it was necessary to set a time limit on the return of the equipment. A paper parachute of about five feet in diameter was attached to the equipment to ensure safe recovery of the plates and to eliminate property damage from too rapid a descent. All of the balloons were heat treated by immersing them in water above 80°C. for about five minutes before they were inflated.

The free lift of the balloons was adjusted by controlling the amount of helium to the balloons. The equipment was weighed and a dummy load was made which could be attached to the inflation nozzle of the balloons. The balloons were inflated with helium in the Armory and released in the open area west of the building. A total of 19 flights were made with the successful recovery of 14 of the flights. The essential characteristics of these flights are shown in Table I, pages 12 and 13. Baroswitches were included in the flights marked with an asterisk.

In the first flight, the balloon was inflated to give a free lift of 200 grams. The ascension rate, maximum altitude and the rate of descent were obtained from the pressure record. The variation of altitude with time for this flight is given in Fig. 1, page 14. The altitude characteristics of the second and third flights were similar to the first flight. However, in the third flight the ascension rate increased quite rapidly above 20,000 feet. The increase in the ascension rate was probably due to the heating of the balloon by the sun and the subsequent increasing of the free lift.

It was apparent from a study of these flights that a long exposure at high altitudes could not be obtained from this type of balloon flight. Flight number 4 was an attempt to

TABLE I.

Characteristics of Balloon Flights

Flight Number	Number of Balloons	Type of Balloons	Date of Release	Date of Recovery
1*	1	J 350	7/9/49	7/9/49
2*	1	J 350	8/3/49	11/5/49
3*	1	J 500	8/11/49	8/13/49
4	2	J 500 1400	4/17/50	4/26/50
5	2	J 500 1400	8/11/50	8/17/50
6	3	J 500 1400	8/17/50	8/17/50
7	4	J 350 500	8/20/50	8/20/50
8*	5	J 800 500	9/22/50	9/23/50
9	5	J 500 1400	10/2/50	
10*	1	J 800	10/9/50	
11*	2	J 500	10/13/50	10/14/50
12*	2	J 500	10/18/50	10/25/50
13	1	J1400	10/25/50	12/20/50
14	1	J 800	10/30/50	11/7/50
15	1	J1400	11/13/50	11/15/50
16	1	J1400	11/15/50	12/9/50
17	1	J 800	11/17/50	
18	1	J 800	11/18/50	
19	1	J1400	11/29/50	

TABLE I (Continued)

Flight Number	Time of Release	Distance Trav. Mi.	Place of Recovery	Max. Alt. in Feet	Time Above 50,000 Ft.
1*	11:20	60	Garwin, Ia.	60,000	$\frac{1}{2}$
2*	8:55	100	New Vir., Ia.	40,000	
3*	8:04	60	Toledo, Ia.	50,000	
4	9:00	320	Batch, Ill.	90,000	4
5	8:00	90	Ottumwa, Ia.	?	$\frac{1}{2}$
6	7:30	60	Toledo, Ia.	70,000	$\frac{1}{2}$
7	7:00	170	Moline, Ill.	?	$\frac{1}{2}$
8*	7:30	75	Oskal., Ia.	80,000	$1\frac{1}{4}$
9	20:00	?			
10*	17:50	?			
11*	16:40	230	Lewistown, Ill.	54,000	
12*	16:10	210	Broadhead, Wisc.	60,000	
13	15:30	900	Oneida, N. Y.	50,000	
14	14:55	270	Butler, Mo.	80,000	3
15	16:00	120	Iowa City, Ia.	70,000	$\frac{1}{2}$
16	14:30	1,166	Chicoutimi, Que.	80,000	6
17	15:00	?			
18	14:45	?			
19	15:00	?			

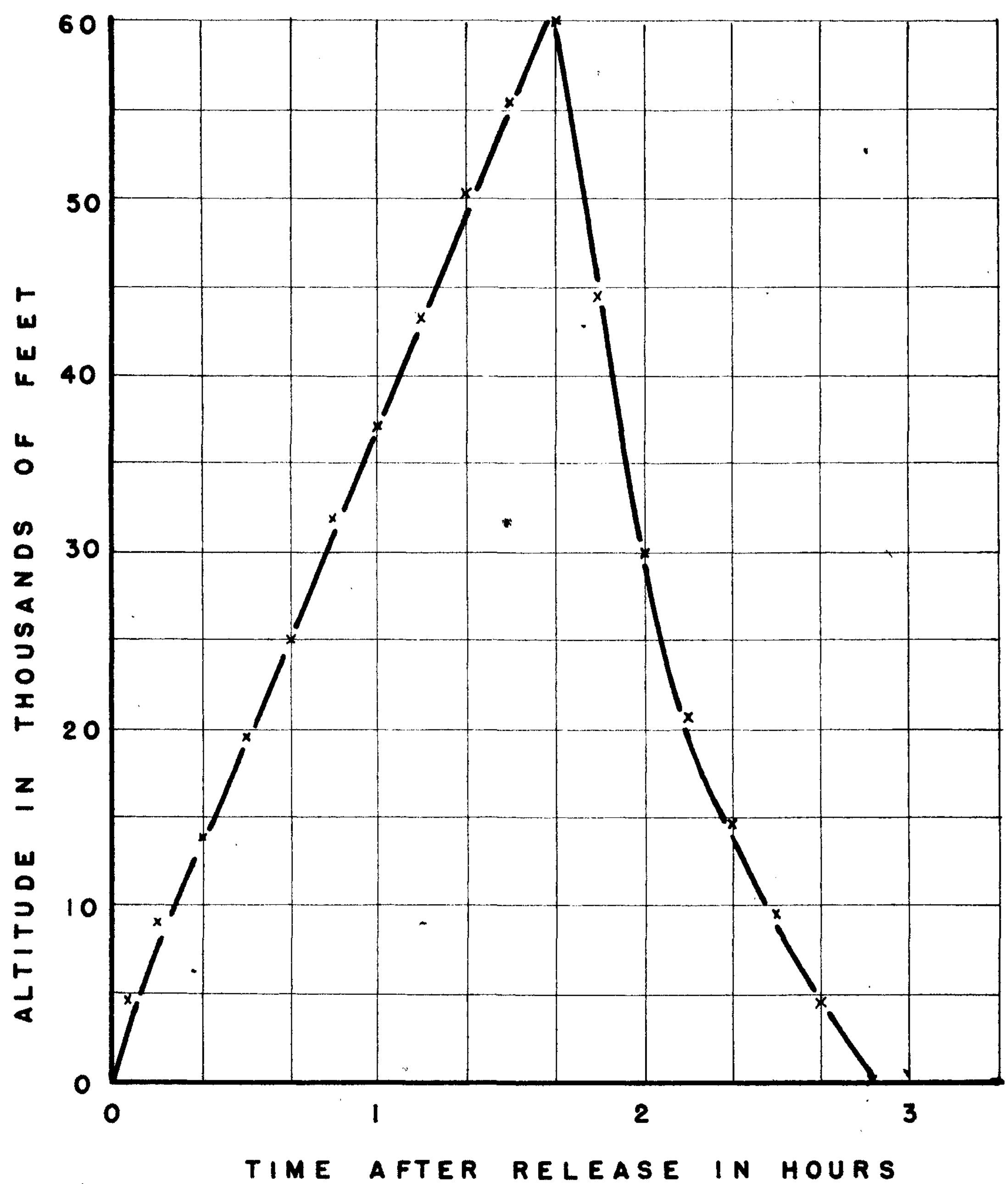


Fig. 1. Variation of altitude with time for flight number 1.

obtain equilibrium at high altitudes by having one balloon break, thereby decreasing the free lift nearly to zero. The next four flights were made in a further attempt to achieve this condition. The altitude record from flight number 8 showed that the free lift increased with altitude with the result that the free lift was much greater than zero after the first balloon broke. The remaining balloons continued to ascend until additional balloons broke. The free lift was never small enough for the balloons to remain at a constant altitude. There seemed to be no simple basis for correctly estimating the change in the free lift of the group of balloons.

Next, an attempt was made to keep the balloons at high altitudes by utilizing the change in free lift due to the solar heating of the balloons. The balloons were released in the early afternoon with a small free lift. It was expected that the free lift would increase due to solar heating. The releases were so timed that sunset would occur before the balloons reached their bursting altitude. The balloons then cooled off due to the excess thermal radiation from the balloons as compared with the surrounding air. The free lift then decreased and the balloons remained nearly at a constant altitude for several hours.

Unfortunately, the details of the ascension rates of these flights are not known. Pressure recording devices were not included in the flights. The increase in exposure time at high altitudes is apparent from the meson density in the plates and from the linear distance that the balloons traveled.

IV. NUCLEAR EMULSIONS

A. Processing

The basic action of the developer, short stop, and fixer for nuclear track plates is essentially the same as for ordinary photographic plates. However, the technique for developing the plates must be modified to ensure uniform development throughout the entire thickness of the emulsion. The method devised by Dilworth, Occhialini and Payne[12] was used to develope all of the plates. The developer was impregnated into the emulsions by soaking the plates in stock D-19 for 35 minutes at a temperature near $0^{\circ}C$. The low temperature was maintained by placing the developing tray in an ice bath during the impregnation process. At temperatures near zero, development did not occur. The plates were then removed from the developing solution and the excess developer on the surface was removed by blotting. The plates were developed by placing the plates on a brass block for 35 minutes. The heat capacity of the brass block was great enough to maintain a constant temperature during this period. The development was stopped by rinsing the plates in running water for 25 minutes.

The emulsions were hardened and fixed by immersing the plates in a conventional fixing solution for a period of about 8 hours. The fixing solution was strongly agitated during the fixation process. The plates were then washed for five hours under running water. Before the plates were dried, they were dipped in a solution of 2% glycerine, to prevent the thick emulsions from peeling from the glass supports. The plates were stored in a container where the relative humidity was kept above 50%. Under these conditions, there has been no tendency for the emulsions to peel.

B. Searching

A total of 47, 1" x 3" nuclear track plates were searched for meson events. A Bausch and Lomb binocular microscope was used. The motion of the mechanical stage is calibrated in both directions in order that events could be relocated from previously established coordinates. The searching was done with a 8 m.m. objective and a 10x eyepiece. The total magnification was about 200x. With this magnification the field of view was about 7 m.m. in diameter. An entire plate could be searched for meson events in about 4 to 5 hours under normal conditions. On the average about 15 meson events were found in each plate. After a plate was searched and the interesting events were recorded, each event was studied with a magnification of 1000x. Approximately 2.0×10^7 tracks consisting mainly of proton and alpha particle tracks were observed in the 47 plates.

C. Identification of Tracks

The identity of a particle leaving a track in a nuclear emulsion can in many cases be determined from the characteristics of the track, independent of the phenomena at the end of the track. The following quantities can be used to identify a particle: grain density, rate of change of grain density, number and energy of the delta rays per unit length, small angle scattering and its variation along the track, and the total range of the track in the emulsion. Under favorable circumstances, most of the characteristics of a particle such as mass, velocity and charge can be obtained from measurements of the above parameters.

The difference in the appearance of the tracks produced by electrons, mesons and protons is due entirely to difference in the masses of the particles. The mass of the meson is much nearer the mass of the proton than the electron. In general, it would be expected that a meson track would more nearly resemble a proton track than an electron track. This was found to be true. The difference between a proton track and a meson track was found to be small. Two parameters of the tracks were used to separate meson tracks from proton tracks; namely, the rate of change of grain density along the tracks and the many changes in direction of the tracks due to the small angle scattering of the particles. The relationship of these parameters to the mass of a particle will be given in the following discussion.

The rate of energy loss of a non relativistic particle in a nuclear emulsion is given by the following expression[25],

$$-dE/dX = (4\pi e^4 Z^2 N_e/mv^2)\ \log\ (2mv^2/I) \qquad (1)$$

where dE/dX is the energy loss per cm. of path, eZ is the charge of the incident particle, m is the mass of the electron, v is the velocity of the incident particle, N_e is the number of electrons per cubic centimeter and I is the average excitation potential of the atom. The variation of the logarithmic term will be neglected in the following discussion.

Consider a particle of mass M, charge Z and velocity V entering a photographic emulsion. The range of this particle is given by the following equation.

$$R = \int_0^R dx = \int_E^0 (dx/dE)dE \quad \int_0^V \frac{MV\ dV}{-dE/dx} \qquad (2)$$

Substitution of the value for dE/dx from the equation (1) into the above equation gives the following equation.

$$R = (M/Z^2)\ f(V) \qquad (3)$$

where f(V) is a function which depends upon the velocity of the particle. The range of the particle is proportional to the mass of the particle and inversely proportional to the square of the charge of the particle for a given velocity. For a π meson and a proton of the same velocity, the range of the proton will be approximately 7 times greater than the range of the π meson. Equation (1) shows that the energy loss of a proton and a meson will be the same when the velocities of the two particles are the same. In a photographic emulsion the grain density along the track is proportional to the rate of energy loss of the particle which caused the track. The grain density along a proton track and a meson track will then be the same where the velocities of the two particles are the same. Since the meson track will be much shorter, the rate of change of grain density along the meson track will be greater than along the proton track. This characteristic of meson tracks is one of the criteria used to distinguish mesons from protons.

The average angle of scattering per unit length along the track of a charged particle is given by the following equation[26],

$$\bar{a} = A\,(1 - \beta^2)^{\frac{1}{2}} / M\beta^2 c^2 \qquad (4)$$

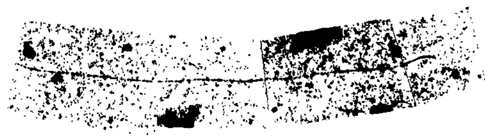
where $\bar{a}$ is the average angle of scattering for a given interval, A is a constant which is a function of the emulsion and the length of the interval considered, β is the ratio of the velocity of the particle to the velocity of light, and c is the velocity of light. For particles of comparatively low velocities, equation (4) becomes,

$$\bar{a} = A / M v^2 \qquad (5)$$

where M is the mass and v is the velocity of the scattered particle. A meson and a proton of equal velocities will produce equal grain densities along their tracks. However, the average angle of scattering of the meson will be about 7 times larger than the average angle of scattering of the proton. This relationship was used, along with the rate of change of grain density, to distinguish meson tracks from proton tracks. Fig. 2a and Fig. 2b are microphotographs of a proton and a meson track taken with the same magnification. The larger amount of small angle scattering of the meson track is quite apparent.

Using the above criteria, 659 meson events were found in the plates. Of these mesons, 500 are mesons which stop in the emulsion without associated particles other than electrons, 118 are negative π mesons causing stars, and 41 are π mesons which decay into μ mesons.

An example of a π-μ-e decay is shown in Fig. 4. Fig. 5 is a mosaic of a star caused by an energetic heavy nucleus. Two cones of mesons can be observed in the forward direction of the heavy nucleus.

A. 

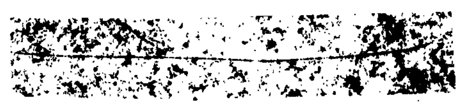
B. 

Fig. 2. Photomicrograph of (A) a meson which stops in the emulsion, (B) a proton which also stops in the emulsion. If it is assumed that track 2a is due to a meson, the velocity for a given residual range is higher for the meson, even so the meson exhibits a large amount of small angle scattering.

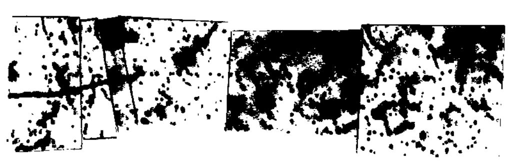


Fig. 3. Mosaic of a μ meson decay. The heavy track to the left is the meson track. The light track to the right is presumably the track of the decay electron.

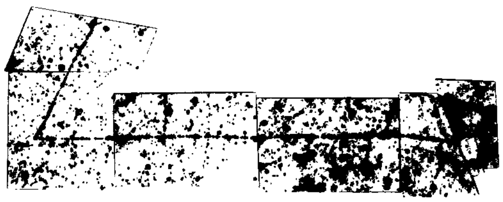


Fig. 4. A mosaic of a π-μ-e decay. The π meson enters from the upper left. The μ meson travels to the right. About 5 grains along the decay electron track are to be seen above and parallel to the end of the meson track.

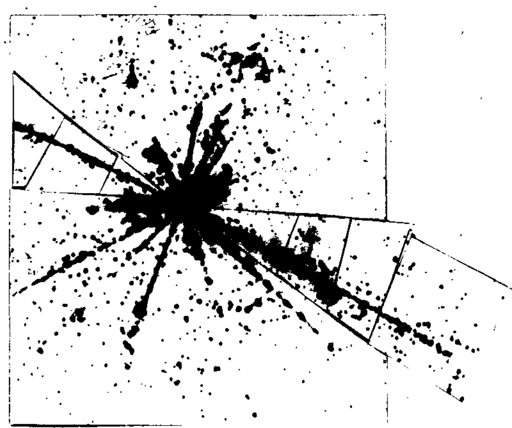


Fig. 5. A mosaic of a star caused by an energetic heavy nucleus. The track of the nucleus is to the upper left of the center of the star. Two sets of minimum ionizing tracks are very probably meson tracks.

V. μ MESONS

A. Decay of μ Mesons

All mesons which stopped in the emulsion without associated particles other than electrons, were classified as μ mesons. Using this criterion, a few π mesons were included as μ mesons. The sensitivity of the emulsion was great enough that the tracks of the μ mesons from the decay of the π mesons could be seen even though the meson tracks were nearly vertical. Thus, very few if any of the π mesons which decayed into μ mesons in the emulsion were classified as μ mesons. However, it is known that 26.8% of the negative π mesons are captured by nuclei without producing stars[27] in photographic emulsions. These negative π mesons were included in the 500 mesons which stopped in the emulsion with no associated particle other than electrons. Since 118 negative π mesons which produced stars were observed in the plates along with the 500 mesons, about $(118)(0.268)/(0.732) = 43$ negative π mesons were included in the 500 mesons which stopped in the emulsion with no associated particles other than electrons.

A careful search was made with high magnification for minimum ionizing tracks at the end of the μ meson tracks.

It has been shown[9] that the minimum ionizing tracks originating from the end of the μ meson tracks are due to high energy electrons from the decay of the μ mesons. These tracks were very difficult to observe, since the grain density along the tracks is very nearly the same as the random background. Only those tracks which were nearly in the plane of the emulsion could be seen.

Out of a total of 500 mesons only 462 were found in plates which were suitable from sensitivity considerations for observing the decay electron. Of these mesons, only 462 - 43 (462/500) = 422 are actually μ mesons. At the end of 122 meson tracks a minimum ionizing track was observed. A typical meson decay is shown in Fig. 3, page 24. An estimate can be made in the following way of the number of decay electrons that were not observed. A study was made of 102 of the 122 tracks. The angles made by the observed decay electrons with the plane of the emulsion were measured. A histogram was made of the number of electrons within an angular interval for a given angle with the plane of the emulsion. The result is shown in Fig. 6,

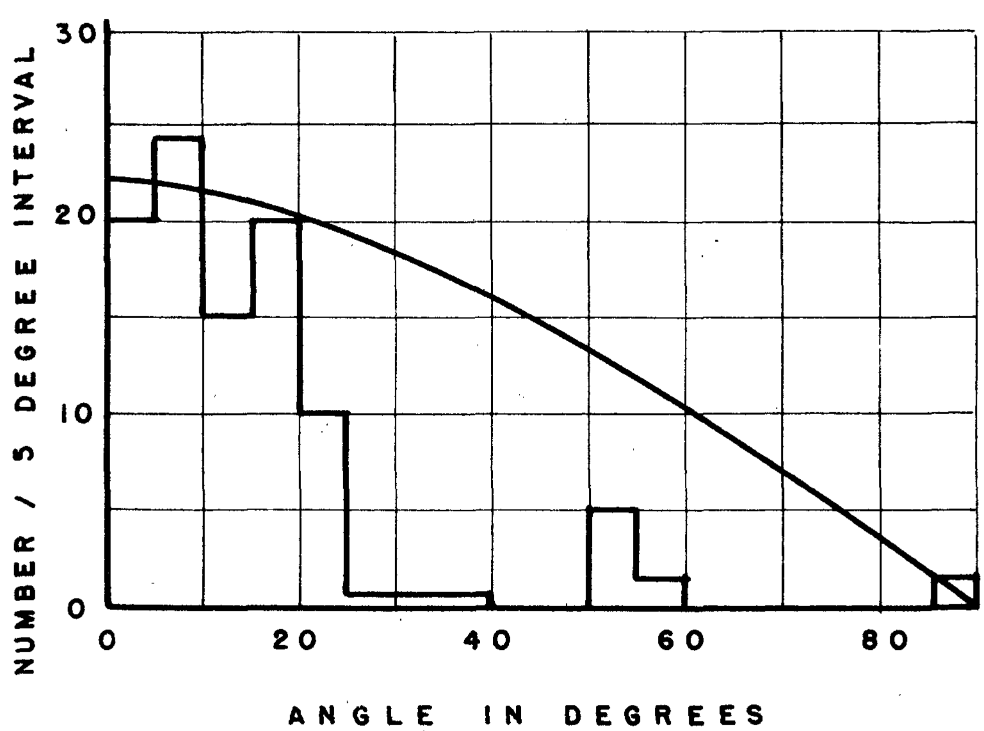


Fig. 6. Histogram of the number of decay electrons in a given angular interval as a function of the angle made by the tracks with the plane of the emulsion.

page 28. A cosine curve, representing a constant solid angle, was superimposed on the histogram, with the ordinate at small angles equal to the ordinate of the histogram. Assuming that all the electrons were observed which made a small angle with the plane of the emulsion and that there were equal numbers of electrons in a given solid angle, then the area between the cosine curve and the histogram represents the number of decay electrons which were not observed. In this manner it was estimated that 166 decay electrons were emitted in such a direction that the tracks were not observed. A total of $166 + 122 = 288$ μ mesons presumably decayed in the emulsion ($68 \pm 7\%$). Cosyns, Dilworth, Occhialini and Schoenberg[22] found that $63 \pm 4\%$ of the mesons decayed in the emulsion. Bonetti[23] found that 68% of the mesons which stopped in the emulsion gave rise to a decay electron. However, the percentages given by Cosyns et al. and Bonetti include as μ mesons the negative π mesons which did not produce stars.

The probability (122 out of 288) of observing minimum ionizing tracks from mesons is in rough agreement with the results of a study of the number of decay electrons from μ

mesons which in turn were observed to originate from π mesons. It has been shown that essentially all of the negative π mesons which stop in photographic emulsions are captured and do not decay into μ mesons[30]. Then nearly all of the π mesons which decayed into μ mesons in the emulsion were positively charged. All of these μ mesons would then be expected to decay into an electron. Out of a total of 41 cases of π-μ decays that were observed in the emulsion, 14 were observed where the μ meson stopped in the emulsion. The decay electron was observed from 9 of these 14 cases, which is not inconsistant with the above.

The percentage of the μ mesons that would be expected to decay in photographic emulsions can be estimated in the following manner. The emulsion consists of a group of heavy elements principally silver and bromine, in the form of crystals, and a lighter group consisting of hydrogen, carbon, nitrogen and oxygen in the form of gelatine. Assuming that the stopping power for low energy mesons by various materials in the emulsion is proportional to the atomic number, it is estimated from the composition* that 79% of the mesons stopped in silver bromide crystals and 21% stopped in the gelatine.

*The composition of the emulsion is given in Appendix A.

Of the 422 μ mesons, on the average 334 stopped in silver bromide crystals, while 88 stopped in gelatine. Experimental evidence has shown that there are about equal numbers of positive and negative μ mesons in the low energy spectrum from cosmic rays[28] at sea level. It seems not unreasonable to assume equal numbers of positive and negative μ mesons at higher altitudes. This assumption is strengthened by the satisfactory agreement between the percentage of mesons which decayed in plates exposed at mountain heights with the percentage found at higher altitudes. Of the 88 mesons which stopped in gelatine, about 44 are negative mesons. From theoretical considerations[29] it has been shown that the probability of nuclear capture[29] of a negative meson is proportional to Z^4. It has been found that mesons stopped in materials of $Z = 10$ have about equal probabilities of capture and decay. Then essentially all of the negative mesons which stopped in silver and bromine were captured and did not decay while almost all of the negative μ mesons which stopped in gelatine would be expected to decay. A total of $44 + 211 = 255$ would be expected to decay. A total of 288 were observed.

B. Low Energy Electrons

A careful search was made for low energy electron tracks which originated from the end of the 500 meson tracks which stopped in the emulsion without associated tracks other than electrons. All of the plates were suitable for the study of low energy electrons. A total of 58 (11.6%) of the mesons have one or more associated low energy electrons. Of the 58, 10 of the mesons have two low energy electrons originating from the same meson. In two cases (0.4%), three low energy electrons were observed. Two examples of a low energy electron associated with a meson are shown in Fig. 7 and Fig. 8, page 33. The energies of the electrons were determined from their ranges. Tracks of low energy electrons are very crooked. The total length was determined from measurements of the length both in the horizontal and the vertical planes. Corrections were made for the vertical shrinkage of the emulsion.

The energy distribution of the low energy electrons from these mesons is shown in Fig. 9, page 34. There is no evidence of detailed structure. The energy distribution can be well represented by the equation, $N(E) \sim \exp. (-E/E_a)$ where

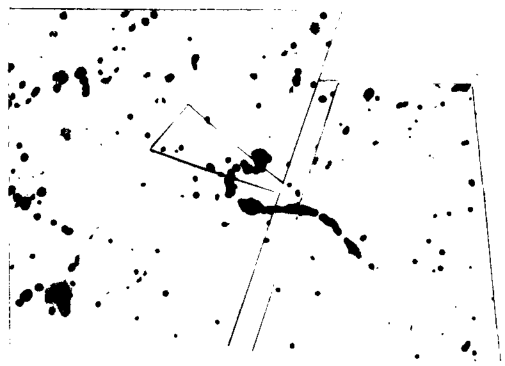


Fig. 7. Mosaic of a meson track which has an associated low energy electron track and a "blob." The meson track goes upward to the left. A clump of silver grains can be seen at the end of the meson track. The track of an electron can be seen above the meson track.

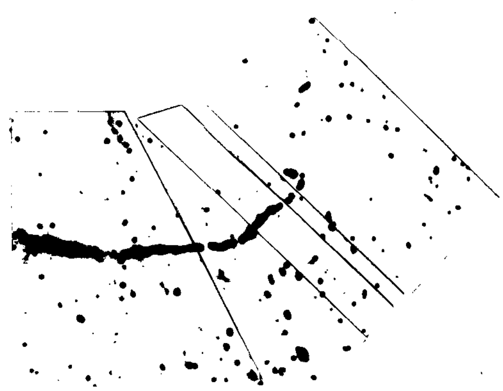


Fig. 8. A mosaic of a 35 k.e.v. electron track associated with a meson. The meson enters from the left. The track of the electron is to the right and above the end of the meson track.

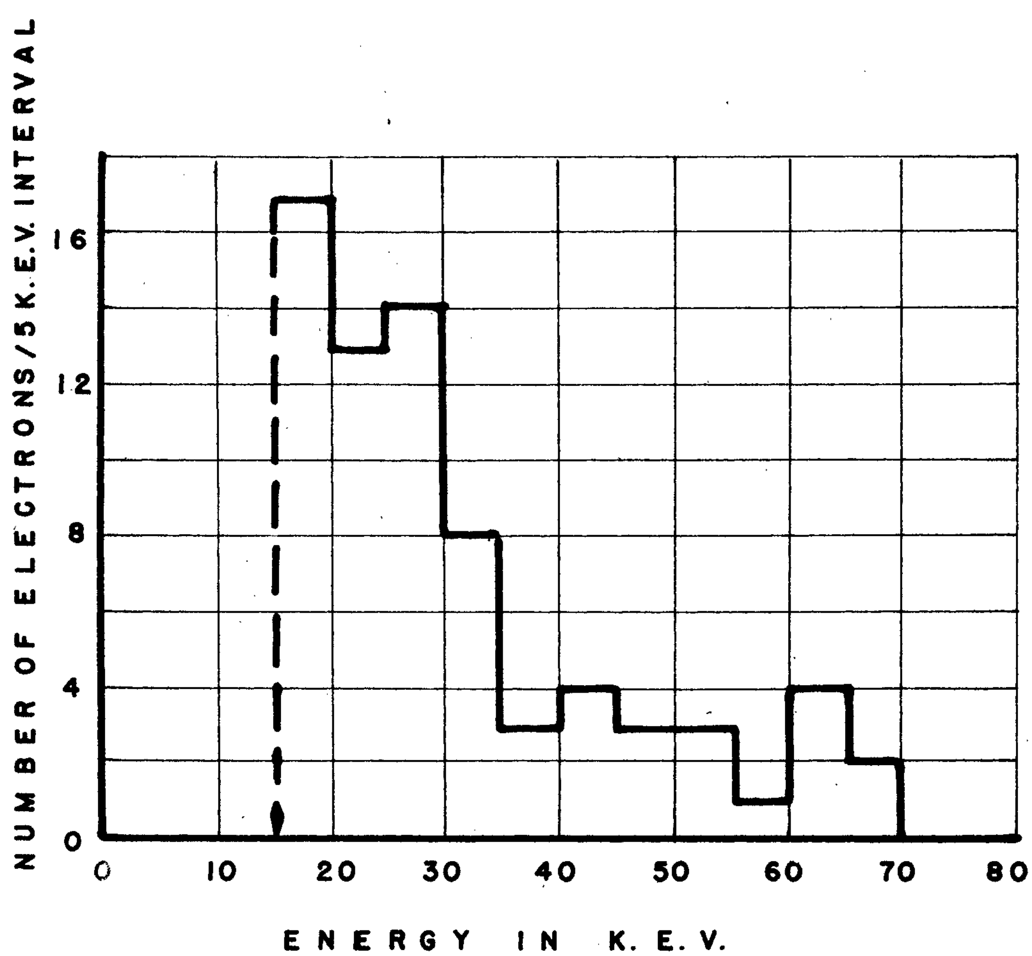


Fig. 9. Energy histogram of the low energy electrons from mesons which end in the emulsion without associated particles other than electrons.

E_a is an average energy and has a value of about 17 k.e.v.

Many background electrons were present in the plates. A rigid criterion was established for admitting electrons as being associated with the mesons, in order to estimate the importance of the background electrons. Only electron tracks which originated within 2 microns of the end of the meson tracks were considered as being associated with the mesons. Using this criterion, an estimate of the number of electrons accidentally associated with the mesons was made in the following manner. A total of 300 proton tracks were found which originated from stars and stopped in the emulsion. A low energy electron was erroneously considered to have originated from a proton track only in two cases; hence the background can be neglected.

It is difficult to determine the number of low energy electrons from these mesons that were not seen. Many background tracks with energies less than 100 k.e.v. were studied in the emulsion. Even those tracks which were nearly vertical could be followed. From this study, it appears that very few electrons in the energy interval from 15 to 70 k.e.v. were omitted. The contribution to the number of low energy electrons from negative π mesons erroneously considered as μ mesons is discussed in section VI.

C. "Blobs"

At the end of 32 meson tracks a clump of silver grains was observed. At the end of the 32 meson tracks which have a "blob", 27 also have one or more low energy electrons. The "blobs" were not seen at the end of 122 μ mesons which decayed nor at the end of 41 π mesons which decayed into μ mesons. The bulk of the μ mesons which decayed was composed of mesons which were positive. Essentially all of the π mesons which decayed into μ mesons were positive. From these facts it is apparent that the "blobs" are associated with negative mesons, rather than large angle scattering of the mesons near the end of their range [28, 30]. It is thought that the "blobs" are due to one or more electrons of very low energy ($E < 15$ k.e.v.).

Since the probability of producing "blobs" by an electron of energy less than 15 k.e.v. is unknown, it is not possible to form an estimate of the number of electrons of energy less than 15 k.e.v.

A photograph of a meson which has a clump of silver grains at the end of its range is shown in Fig. 10, page 37.

Fig. 10. Photomicrograph of a meson which ends in the emulsion. A clump of silver grains can be seen at the end of the meson track.

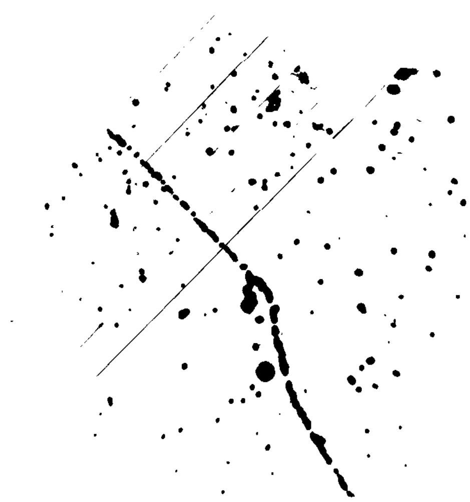


Fig. 11. A mosaic of a one prong star caused by the nuclear capture of a negative π meson. The meson track enters from the bottom of the mosaic and a track of a proton can be seen above the end of the meson track. A track of a low energy electron can be seen to the left and below the end of the meson track.

VI. MESON INDUCED STARS

In 118 cases, meson tracks were found to end in stars. A careful search was made for low energy electrons (15 k.e.v. $< E <$ 70 k.e.v.) associated with these stars. In 22 cases (19 $\pm$ 4%), one or more electrons in the energy interval from 15 to 70 k.e.v. were observed. In 4 cases, two low energy electrons were observed from the same star. The energy histogram of the low energy electrons from negative π stars is shown in Fig. 12, page 39. A microphotograph of a typical meson star with an associated low energy electron is shown in Fig. 11, page 37.

A search was made for minimum ionizing tracks from meson stars. No minimum ionizing tracks were seen. A particle would produce a minimum ionizing track if the kinetic energy were nearly equal to or greater than its rest energy. In the case of meson stars, the available energy is the rest energy of the negative π meson. The only particles that would produce minimum ionizing tracks under these conditions are electrons. The probability of observing a minimum ionizing track can be estimated from the study of the decay electrons from μ mesons. From a total of 288 μ mesons which presumably decayed, only 122 decay electrons were observed.

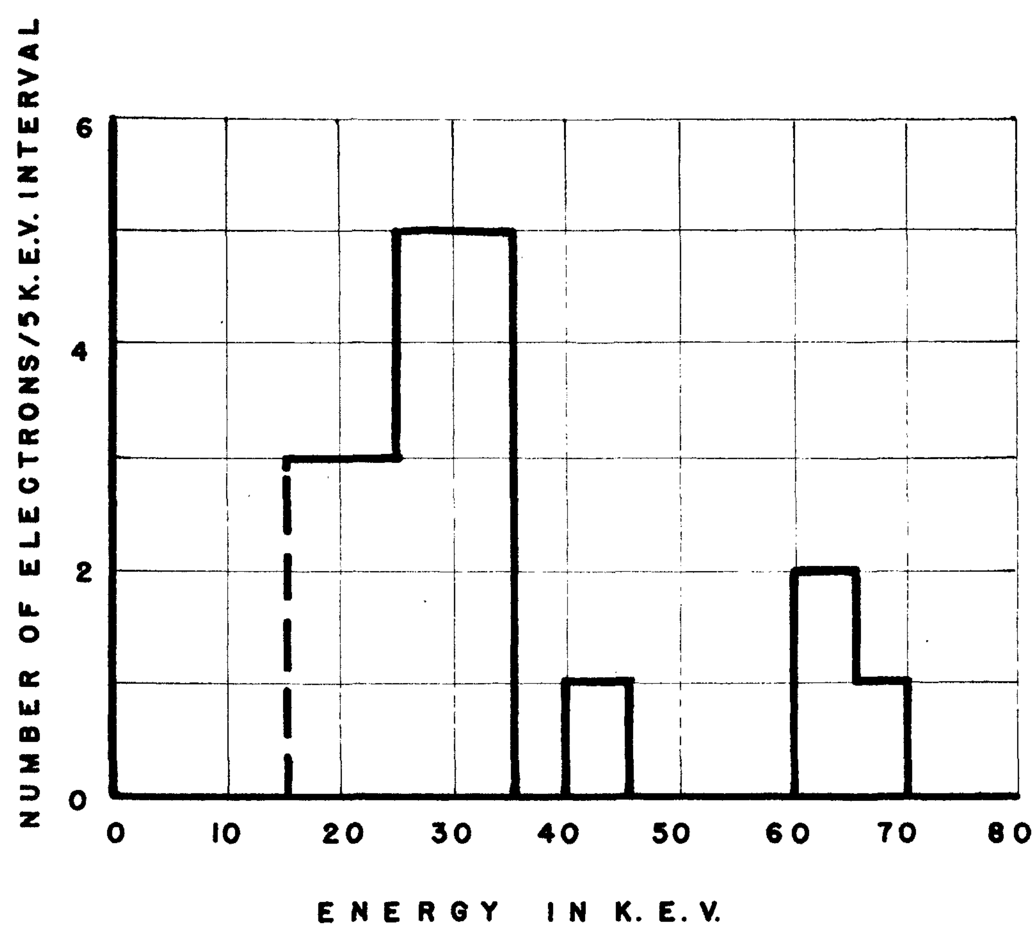


Fig. 12. Energy histogram of the low energy electrons from meson stars.

Thus, the probability of seeing a minimum ionizing track is about 0.4. From these facts one concludes that the β activity of the residual nucleus from meson stars must be very small ($E_e > 0.2$ m.e.v.).

In 6 cases a clump of silver grains was observed at the center of the meson stars. The clumps are very similar to the "blobs" that were observed at the end of the meson tracks which have only associated electron tracks. For the case of stars of more than two prongs the "blobs" were probably masked by the clustering of the silver grains due to the proximity of the tracks from the star.

A slightly more accurate estimate can now be made of the contribution to the number of low energy electrons by the π mesons which did not produce stars. Of the 500 mesons, about 43 are negative π mesons. Of these 43 mesons, on the average $(43)(0.19) \cong 8$ have an associated low energy electron. Of the total of 58 mesons which have one or more associated low energy electrons, only 50 ($11 \pm 1.5\%$) are actually μ mesons.

A total of 41 π mesons which decayed into μ mesons were observed in the plates along with 118 meson stars. These data indicate that the ratio of negative to positive mesons is $(118/41) \cong 2.9$ for these altitudes. This ratio has been determined by Franzinetti[28] who found the ratio to be $(19/14) = 1.35$ for an altitude of 3,500 meters. Bonetti[23] found the ratio of negative to positive π mesons to be $(89/45) \cong 2$ for an altitude of 2,800 meters. Brown[9] et al. found the ratio to be $(30/30) = 1$ for an altitude of 3,500 meters. It does not seem unreasonable to assume that this ratio changes with altitude.

VII. RANGE-ENERGY RELATIONSHIP

The ranges of electrons of various energies have been determined by Zajac and Ross[10] for Ilford emulsions and by Hertz[11] for NT4 emulsions. Range-energy data were not available for electrons of energy below 30 k.e.v. It is to be expected that the mean range of electrons of a given energy will vary with the type of emulsion. For these reasons it seemed desirable to make a study of the range-energy relationship for low energy electrons in NTB-3 plates.

Nuclear plates were exposed to monoenergetic electrons of 50 k.e.v. in a R.C.A. electron microscope. The accelerating potential was found by measuring the current through a high resistance bleeder incorporated in the instrument. The horizontal lengths along the crooked tracks of the electrons were measured by a calibrated scale in the eyepiece of the microscope. Vertical dimensions were measured by the scale attached to the fine adjustment of the microscope. The scale in the eyepiece of the microscope was calibrated by observing a diffraction grating of known spacing.

Additional plates were exposed to monoenergetic electrons of 30 k.e.v. and 20 k.e.v. in a conventional instrument built by G. E. for electron diffraction studies. The plates were processed by the same technique as the plates from the balloon flights.

It is well known that the vertical shrinkage of the emulsion depends upon the type of emulsion and the processing. The shrinkage of each plate was determined from measurements of the thickness of the emulsion after the plates were processed. The uniformity of shrinkage throughout the depth of the emulsion was checked in the following manner. Tracks of energetic particles were found in the plates which made an angle with the plane of the emulsion of about 10 degrees. Since the particles were energetic, the tracks would not be expected to show any large angle scattering. The angle made with the plane of the emulsion was measured at several depths. Only if the vertical shrinkage of the emulsion were uniform would this angle be the same at all depths in the emulsion. For the 5 tracks that were measured, the angles made by the tracks with the plane of the emulsion were constant throughout the depth of the emulsion ($\pm$ 5%). A reliable shrinkage factor for the emulsion can then be obtained from a measurement of the thickness of the plate after processing.

The average range of each group of monoenergetic electrons was found. The results are in reasonable agreement with the published work of Zajac and Ross[10] who found the mean range of 50 k.e.v. electrons to be 15.8 ± 0.5 microns. For 30 k.e.v. electrons the average range was found to be 7.0 ± 0.3 microns.

TABLE II

Range-Energy Relationship

Energy in k.e.v.	Number of Tracks	Mean Range in Microns	Spread in Energy
50	35	17.5	± 6
30	50	7.0	± 4
20	50	3.7	± 4

The distribution in range for the three groups of monoenergetic electrons is shown in Fig. 13, Fig. 14, and Fig. 15.

These data were plotted and a smooth curve was drawn through the points. The apparent energy of each electron was determined from the range in the emulsion. A histogram of the apparent energy distribution of the three groups of

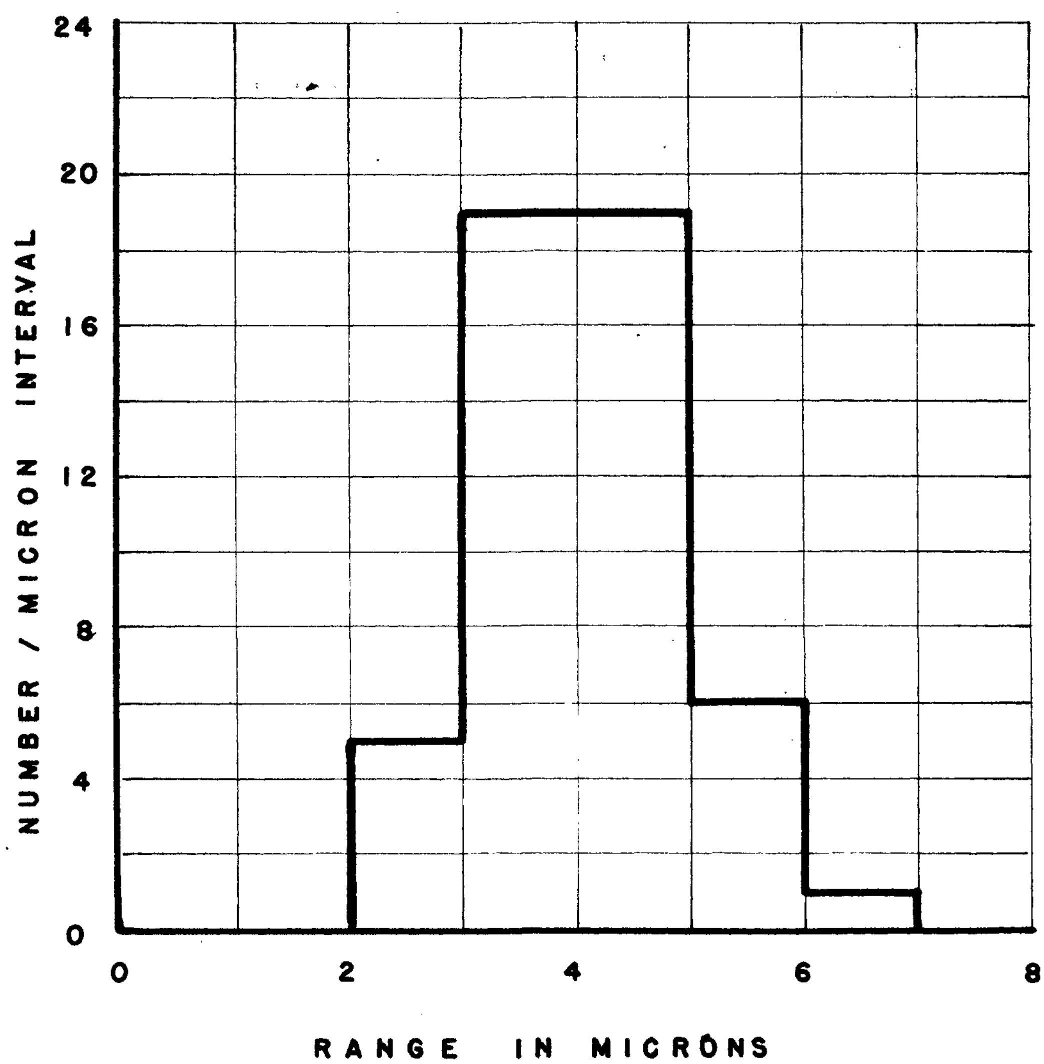


Fig. 13. Range histogram of 20 k.e.v. monoenergetic electrons.

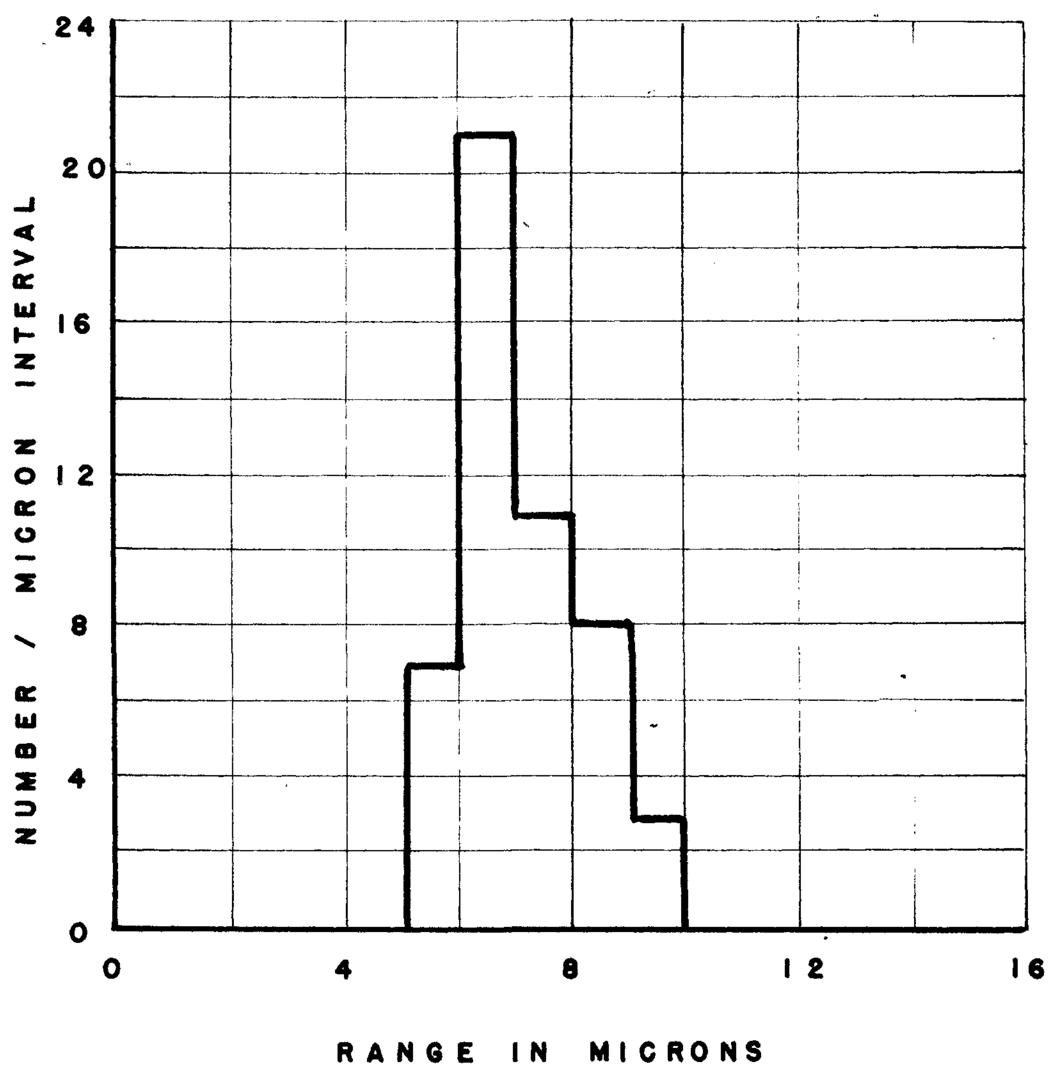


Fig. 14. Range histogram of 30 k.e.v. monoenergetic electrons in NTB-3 emulsion.

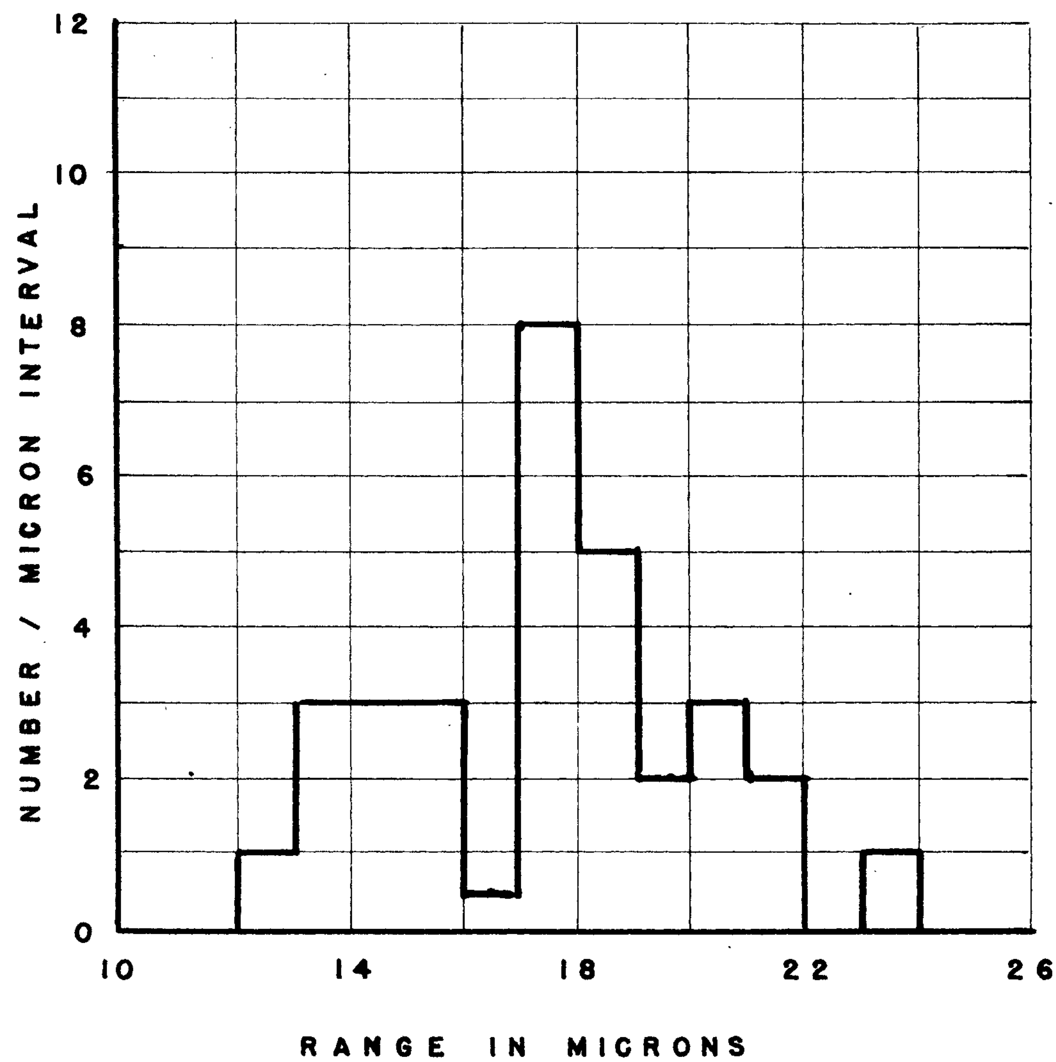


Fig. 15. Range histogram of 50 k.e.v. monoenergetic electrons in NTB-3 emulsion.

monoenergetic electrons is shown in Fig. 16, page 49. It is seen that the energy resolution of the emulsion for electrons of energy less than 30 k.e.v. is quite poor. Detailed line structure could not be detected from range measurements of electrons below 30 k.e.v.

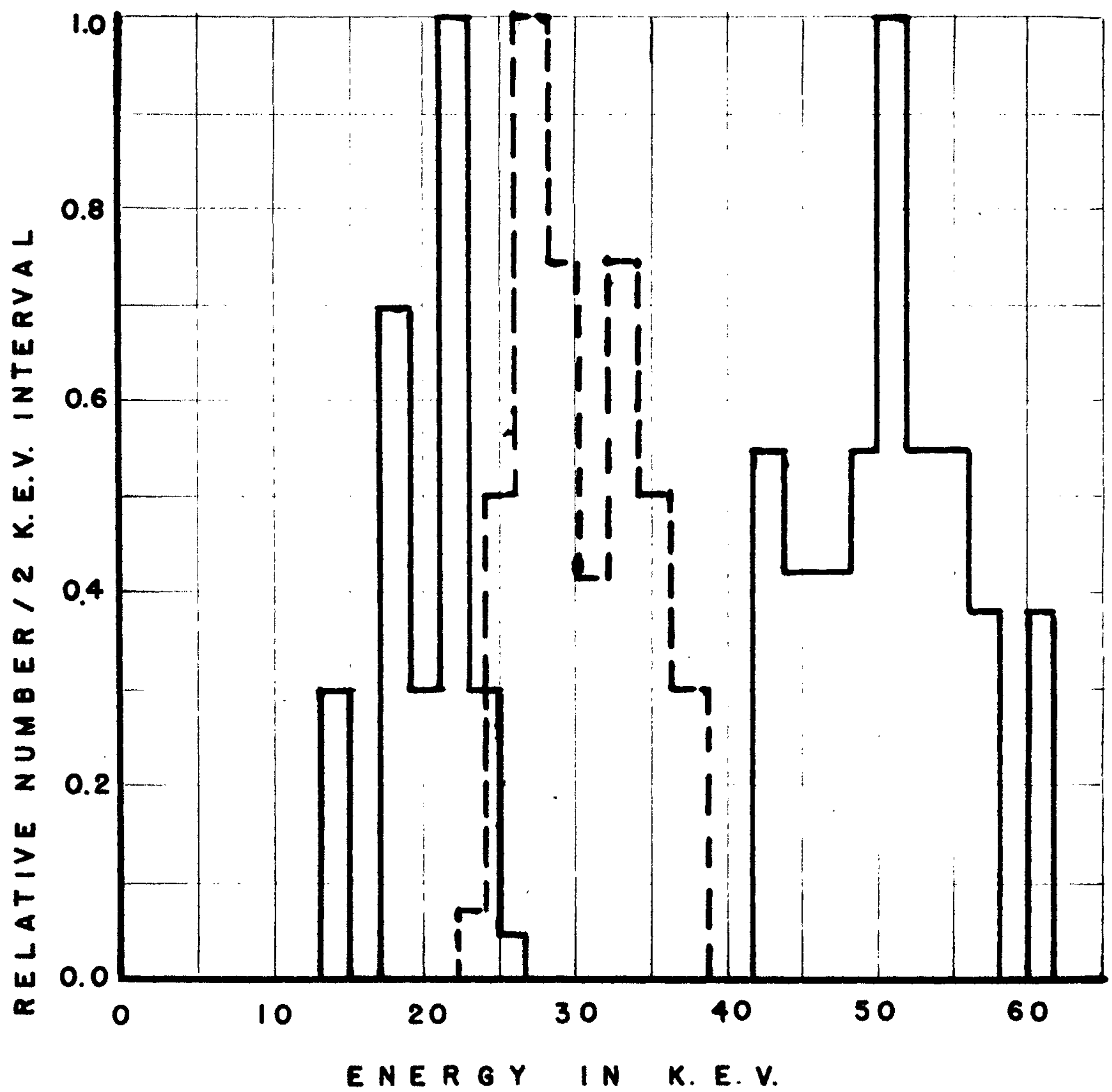


Fig. 16. Apparent energy histogram of three groups of monoenergetic electrons.

VIII. SUMMARY AND CONCLUSIONS

Nuclear track plates were exposed to cosmic radiation in the stratosphere by means of meteorological balloons. A careful search was made for meson tracks which stopped in the emulsion. The phenomena at the end of the meson tracks were studied and the following data were obtained.

A total of 659 meson events have been studied. Of these mesons, 500 are mesons which stopped in the emulsion without associated particles other than electrons, 118 are negative π mesons which end in stars, 41 are π mesons which decay into μ mesons. Since 118 negative π mesons and 41 positive π mesons were observed in the same plates, there seems to be a ratio of 1 to 3 of positive to negative π mesons at these altitudes.

A total of 422 μ mesons were found which stopped in the plates that were suitable for observing the decay electron. The decay electron was observed from 122 of these mesons. From the angular distribution of these electrons it was estimated that 166 decay electrons were not seen. Thus 288 μ mesons presumably decayed in the emulsion ($68 \pm 7\%$).

A careful search was made for low energy electron tracks originating from the end of the meson tracks. One or more electrons in the energy interval from 15 to 70 k.e.v. were observed to originate from 58 mesons which stopped in the emulsion without producing stars. From a study of negative π stars it is estimated that about 8 of these cases are due to negative π mesons. Thus about 50 μ mesons out of a total of 457 μ mesons have one or more associated low energy electrons ($11 \pm 1.5\%$). From a study of the accidental association of the background electron tracks with proton tracks which stopped in the emulsion, it was found that the low energy electrons associated with the μ mesons can not be ascribed to the background in the plates.

Essentially all of the low energy electrons are associated with μ mesons which did not give rise to a decay electron. This fact indicates that the low energy electrons are associated only with negative mesons. About 21% of the negative mesons stopped in gelatine and would be expected to decay. If the probability of ejecting low energy electrons by mesons which are captured in gelatine is the same as in crystals, then (228)(0.21)(0.22)(0.4) = 4 cases of a low energy electron and a high energy electron should have been observed from the same meson. Since only one low energy electron was observed to originate from a meson which decayed, the low energy electrons are probably associated with the capture of negative μ mesons by silver and bromine atoms.

Of the actual μ mesons which stopped in the emulsion, on the average 228 are negative. Of these 228 negative μ mesons, about 180 were captured by silver and bromine atoms. The probability that one electron in the energy interval from 15 to 70 k.e.v. is ejected upon capture of a negative μ meson in silver or bromine was found to be 0.25 ± 0.04. The probability that two such electrons are ejected was found to be 0.06 ± 0.02. For three low energy electrons the probability was found to be about 0.01. These results are based on the assumption that no positive excess exists for low energy μ mesons at these altitudes.

At the end of 32 μ meson tracks a clump of silver grains was observed. These "blobs" indicate that in many cases electrons of energy less than 15 k.e.v. are associated with the capture of negative μ mesons.

The capture of negative π mesons in photographic emulsions does not lead to residual nuclei which are β active ($E > 0.2$ m.e.v.) since no minimum ionizing tracks were seen from 118 meson stars.

One or more low energy electrons were observed to originate from 22 out of a total of 118 stars caused by negative π mesons. The probability that a negative μ meson eject one low energy electron upon capture in silver or bromine was found to be 0.24 ± 0.06. The probability of ejecting two such electrons was found to be about 0.04. The energy distribution of the low energy electrons from meson stars is about the same as the distribution from μ mesons. The probability that a negative π meson which stops in a photographic emulsion will give rise to a low energy electron is within statistical limits the same as for a negative μ meson. The residual nucleus resulting from the capture of a negative π meson is entirely different from a similar nucleus after the capture of a μ meson. These facts indicate that the low energy electrons are due to some type of interaction of the meson with the electronic shells of the atoms, rather than a nuclear phenomenon.

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XI. APPENDIX

A. Composition of Ilford Emulsions*

Element	Z	(atoms/c.c.) x 10^{23}	Percentage of atoms	(% of atoms)
I	53	0.0025	0.3	16
Ag	47	0.1049	12.4	583
Br	35	0.1030	12.18	427
S	16	0.0026	0.31	5
O	8	0.0909	10.75	86
N	7	0.0359	4.26	30
C	6	0.1165	19.69	118
H	1	0.3394	40.13	40

In order to estimate the number of mesons stopped in crystals we take 16 + 583 + 427 + 5 = 1031 divided by 1305 which is the total of column 5, and thus obtain 0.79. The fraction stopped in gelatine is 0.21.

B. Composition of Photographic Solutions

Developer

5.5	grams	Metol
180.0	"	Sodium Sulfite
22.0	"	Hydroquinone
120.0	"	Sodium Carbonate
10.0	"	Potassium Bromide

Dissolve in 2500 c.c. of water.

*The composition of Eastman emulsions is nearly the same.

Fixer

900 c.c. of water
200 grams Hypo
15 " Sodium Sulfite
15 c.c. Acetic Acid 100%
15 grams Potassium Alum